Part 7

Formation and Evolution of Binary Stars, Brown Dwarfs, and Planets

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Binary Star Formation Simulations

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Abstract. Binary stars provide an excellent calibration of the success or otherwise of star formation simulations, since the reproduction of their statistical properties can be challenging. Here, I summarise the direction that the field has taken in recent years, with an emphasis on binary formation in the cluster context, and discuss which observational diagnostics are most ripe for meaningful theoretical comparison. I focus on two issues: the prediction of binary mass ratio distributions and the formation of the widest binaries in dissolving clusters, showing how in the latter case the incidence of ultra-wide pairs constrains the typical membership number of natal clusters to be of order a hundred. I end by drawing attention to recent works that include magnetic fields and which will set the direction of future research in this area.

Keywords. stars: formation, hydrodynamics, stellar dynamics

1. Introduction

It is often stated that the wealth of data describing the properties of binary stars (e.g. binary and higher order multiplicity fractions, separation, eccentricity, and mass ratio distributions as a function of primary mass) provides some of the most stringent tests of star formation simulations. In this contribution, I review the progress of such simulations, from early calculations which studied fragmentation in isolated cores to the cluster simulations that have dominated the field over the last decade, wherein binaries arise as a natural by-product of the turbulent fragmentation process. I take a critical look at those aspects of the simulations that can be most reliably compared with observations and focus on two areas where the gap between theory and observation is closing, i.e. the mass ratio distribution and the formation mechanism for the widest binaries. I conclude by mentioning recent work which highlights how current models are challenged by the inclusion of magnetic fields at a realistic level.

2. Simulation developments

During the 1980s and 1990s the major focus of binary formation simulations was the study of isolated cores (e.g. Boss & Bodenheimer 1979) and the determination of core properties (e.g. density profile, rotation rate, equation of state, amplitude of perturbation) that would give rise to fragmentation (note that since the initial perturbations were generally of the form m=2, the initial fragmentation was predisposed to involve two objects). Such studies were highly valuable for calibrating different numerical codes and for identifying the stage of the collapse process at which binary fragmentation is liable to occur. They were, however, far removed from their ultimate goal, i.e. of creating binaries whose properties could be compared with observed systems, owing to the fact that it was computationally prohibitive to follow the evolution far beyond the point of initial fragmentation. With typically 10% of the core mass involved in the initial binary fragments, it was impossible to trace out the further evolution of mass and orbital elements that would accompany the proto-binaries' subsequent assembly. A further feature of such simulations was that since they typically involved isolated two-body systems, they did not include the possible role of multi-body dynamics in shaping the ultimate binary population.

The simulations of Bate *et al.* (2002a), Bate *et al.* (2002b) and Bate *et al.* (2003), as well as a large body of broadly similar simulations (Delgado *et al.* 2004a, Delgado *et al.* 2004b, Goodwin *et al.* 2004a, Goodwin *et al.* 2004b, Offner *et al.* 2009), changed the emphasis from isolated binary studies to those in which binaries are formed in the context of cluster simulations. The key technical development here is the implementation of 'sink particles' (Bate *et al.* 1995) which allow collapsed regions to be removed from the domain of detailed computation, replacing them instead by point masses that can gravitationally interact and accrete from the surrounding gas. This permits the creation of binaries whose formation can run 'to completion' (i.e. to the point where they have accreted the bulk of their circumstellar environment) and which can in principle be compared with observed systems. These simulations also emphasise the importance of multi-body dynamics in the early stages of binary formation: the basic unit of star formation in the simulations is the small N cluster, within which binary exchange interactions, and the creation of complex high order multiples, is common.

These simulations generate a wealth of synthetic binary data for comparison with observations. Many have been encouraged to believe that the simulations are essentially 'correct' (despite, in most cases, their omission of key physical effects such as magnetic fields or realistic thermal feedback from the forming stars) since they effortlessly reproduce some basic binary statistics (for example, the increase of binary fraction with primary mass and the wider separation distributions of more massive binaries (see Bate 2009a): both these effects relate to the relative fragility of lower mass systems in the small N cluster environment). Nevertheless, it is worthwhile considering how reliable are the various predictions that arise from such simulations before selecting which are the areas where observational comparison is most meaningful.

In the early days of star cluster simulations (also known as 'turbulent fragmentation' simulations owing to the fact that the initial cloud structure is seeded by realistic levels of supersonic turbulence), the field was monopolised by studies using Smoothed Particle Hydrodynamics (SPH) whose Lagrangian nature was well-adapted to the complex geometries and large dynamic range of densities that develop in such simulations. At this stage, there was much discussion of the physical reality of the copious disc fragmentation that is seen in such simulations (and which creates the small N cluster environment that dominates the subsequent dynamics). Fortunately, the recent development of Adaptive Mesh Refinment (AMR) techniques, and the incorporation of sink particles within AMR (Krumholz *et al.* 2004) has opened up the opportunity for detailed code calibration studies. The results have been encouraging: broadly speaking, provided that the respective resolution criteria of the two classes of technique are respected, the Lagrangian (SPH) and Eulerian (AMR) codes give very similar results (Federrath *et al.* 2010). This encouraging state of affairs is not to say that the copious fragmentation mentioned above is necessarily *physically* correct. Indeed, it is now realised that this behaviour is rather sensitive to the thermodynamical behaviour of the gas and that fragmentation is enhanced in the case that one assumes the simplest (isothermal) equation of state. More recent calculations improve on this barotropic treatment of the equation of state by employing flux-limited diffusion to capture the effect of thermal feedback from the protostars (Bate 2009b, Offner *et al.* 2009). These studies find that a more realistic cooling treatment inhibits disc fragmentation and demonstrate that the early (isothermal) calculations over-predicted the harvest of very low mass stars and brown dwarfs. Note, however, that these simulations do still produce binaries, including close binaries. Typically, close binaries in the simulations are systems that form at large separations and are hardened by a combination of dynamical interactions, accretion, and star-disc interactions.

Having discussed the fidelity with which the initial binary fragmentation is captured, we now turn to how well the simulations follow the evolution of the binary orbital elements as the binary accretes from its environment. We will discuss the accuracy with which the mass ratio distribution is modeled in Section 3 below, but note for now that the binary mass ratio is of course fixed during the time that the bulk of the gas is accreted onto the protobinary and cannot change much once the circumstellar gas is a small fraction of the binary mass. This is, however, not the case for the evolution of the binary separation and eccentricity, where it is well known that discs can be highly efficient agents of orbital evolution when they contain only a small fraction of the binary mass (Lubow & Artymowicz 2000). (This is because discs with internal angular momentum transport processes can convey large fluxes of angular momentum to large radii with relatively little mass). This means that the evolution of separation and eccentricity are also sensitive to the late time evolution of the circumstellar environment and, therefore, depend on how well discs are modeled in the late stages of system evolution. This is an area of relative weakness for the simulations: by focusing on large ensembles of stars, the number of SPH particles per disc is typically only of order 10^4 even when the discs are relatively massive. As discs are depleted by accretion, they become correspondingly more poorly resolved: in particular, once the SPH smoothing length becomes greater than the disc's vertical scale height there can be a large erroneous effect associated with the action of artificial viscosity in the disc which can spuriously accelerate disc evolution. It should be stressed that this is not likely to be an important factor in modeling the initial formation and mass acquisition of binaries but does raise a question mark over using such simulations for the detailed study of eccentricity and separation distributions, for example.

3. The mass ratio distribution of binaries

As noted by Clarke (1996), binary pairing statistics for primaries in different mass ranges allow one to draw some rather general conclusions about the processes that dominate binary formation. If, for example, it were the case that the dominant binary formation mechanism was by the fragmentation of isolated cores into two components then, in the absence of any physical effects that make such a process dependent on the core mass, one might expect the splitting process to be *scale free*: in this case the mass ratio distribution would be independent of primary mass. On the other hand, if the dominant process instead involved dynamical capture within small N clusters, then it turns out that it is the shape of the companion mass function (*not mass ratio distribution*) that should be independent of primary mass.

Although the theoretical prediction is here clear cut, it has turned out to be remarkably difficult to test this observationally, due to the lack of high quality data for systems with widely differing primary masses. The situation for G dwarfs is relatively well characterised, following the pioneering work of Duquennoy & Mayor (1991) and its recent update and extension by Raghavan *et al.* (2010), but it is only recently that the M dwarf samples have been revisited following the study of Fischer & Marcy (1992) (see Reggiani & Meyer 2011, Bergfors *et al.* 2010). There are, however, two factors that complicate the interpretation in the M dwarf case, i.e. both the wide range of primary masses that enter the M dwarf samples and the fact that, since the lower mass primaries are close to the hydrogen burning mass limit, the mass ratio distribution can only be studied over a limited dynamic range. Moreover, it turns out that the companion mass distributions are rather smooth and featureless in both the G dwarf and M dwarf case - in the absence of a particular feature at given companion mass or given mass ratio, it is hard to distinguish the mode of binary formation involved.

Nevertheless, the ongoing improvements in the characterisation of the M dwarf binary population have demonstrated the continuity of binary properties as a function of mass, following previous claims (Thies & Kroupa 2007) that there is a discontinuous change in binary statistics between low mass (M) stars and brown dwarfs (such that the latter apparently show a more marked predilection for equal mass pairs: however, see below). In fact, it turns out that this apparently abrupt change in binary pairing statistics across the hydrogen burning mass limit can be understood in terms of the broad range of primary masses that enter the M dwarf sample. Now that sample sizes have been increased to the point where they can be meaningfuly sub-divided by mass, it turns out that the trend towards more equal mass companions increases smoothly as the primary mass decreases (Bergfors *et al.* 2010). This is as expected for any dynamical process and argues against the 'special' brown dwarf formation mechanism proposed by Thies & Kroupa (2007).

Before leaving the issue of binary mass ratio distributions, it is, however, worth taking a critical look at the claim that brown dwarf binaries have a strong tendency towards equal mass companions (e.g. Siegler *et al.* 2005). This claim is largely based on the results of placing components on colour magnitude diagrams and derived masses using model evolutionary tracks. It is, however, notable that where the component masses are derived dynamically (see the astrometric orbital solutions of Konopacky *et al.* 2010) this tendency to equal mass ratios disappears: indeed the dynamical masses are quite different (and generally much less evenly paired) from the mass estimates deriving from fitting the components to evolutionary models. However, as stressed by Konopacky *et al.* (2010), there are still relatively large error bars on the dynamically derived mass ratios. Thus, any conclusions about the mass ratio distributions in brown dwarf binaries are necessarily very preliminary.

4. Is there an extreme mass ratio problem?

We have seen in the preceding section that there is some uncertainty about the dependence of the binary mass ratio distribution on primary mass. In the case of solar type primaries, however, Duquennoy & Mayor (1991) found a mass ratio distribution that rises towards low $q(= M_2/M_1)$. Although this conclusion was somewhat revised by the re-analysis of closer spectroscopic pairs (with periods less than 3000 days; Mazeh *et al.* 1992), this did not affect the result for the bulk of (wider) pairs: apparently, therefore, binary components typically have rather disparate masses apart from the closest pairs.

This is in stark contrast to the results of numerical simulations which always show a marked preference for the production of more nearly equal mass pairs (e.g. Bate 2009a). This tendency is remarkably insensitive to initial conditions, since it does not derive from the mass ratio of the pair at the time of first fragmentation but instead on the effect of subsequent accretion onto the protobinary pair. This subsequently accreted material usually has higher specific angular momentum than the initial pair and, therefore, first intercepts the secondary's Roche lobe, which is further from the binary centre of mass. The standard result from SPH and ballistic particle simulations dedicated to the evolution of q as a result of accretion (e.g. Artymowicz 1983, Bate & Bonnell 1997, Bate 2000) is that the net effect of accretion is an increase in the binary mass ratio. Thus, it is accretion that drives the mass ratios of binaries in simulations to near unity.

This conclusion has, however, been challenged by more recent grid-based studies (e.g. Ochi *et al.* 2005, Hanawa *et al.* 2010; see contribution by Fateeva *et al.*, this volume). Although these investigations agree that gas preferentially enters the secondary's Roche lobe, it is then found to flow via the L1 point and be finally accreted by the primary. In this case, accretion may drive the mass ratio downwards, and low q pairs are expected to be abundant. These authors suggested that the reason that this effect was not found in previous SPH simulations was a consequence of the excessively viscous nature of SPH, whereby artificial dissipation could allow particles entering the secondary's Roche lobe to avoid escape via the L1 point.

This latter interpretation is, however, unlikely, since subsequent convergence tests of accretion onto protobinaries (Delgado *et al.* in prep.) with SPH demonstrated that - away from shocks - the Jacobi constant (i.e. the Bernoulli function in the rotating frame) is well conserved. Thus, the avoidance of the L1 point cannot be a consequence of dramatic levels of artificial viscosity in the flow's first orbit of the secondary. These convergence tests found that the accretion of high angular momentum material always increases the mass ratio, although they demonstrated that the *magnitude* of this effect is resolution dependent: under-resolution means that the flow in the outer parts of the primary's Roche lobe is not well modeled as a coherent fluid but instead consists of discrete particle orbits which can be captured onto the secondary through L1. This flow from primary to secondary at low resolution means that the *magnitude* of increase of q is likely to have been over-estimated (by about a factor two) in low resolution cluster simulations.

The discrepancy with grid-based codes probably instead derives, at least in large part, from the different flow geometries and temperatures employed. The simulations of Ochi *et al.* (2005) and Hanawa *et al.* (2010) are two-dimensional and rather warm (with isothermal sound speed in the gas being 0.25× the binary orbital velocity). When the SPH simulations are also run with the same temperature and in two dimensions, the results essentially replicate the grid-based findings - i.e. a flow from secondary to primary and a net decrease of q; although the grid-based calculations of Ochi *et al.* (2005) and Hanawa *et al.* (2010) cannot, unfortunately, treat the more realistic cold, three dimensional flows modeled with SPH, this result suggests that q may rise due to accretion after all (see also Val-Borro *et al.* (2011) for a recent grid based study showing accretion driving q upwards).

At first sight, this apparently leaves the problem of creating low q pairs unsolved. However, there are three factors that actually make it questionable whether there is an 'extreme mass ratio problem' after all. Firstly, as noted above, it is almost certain that cluster simulations (in which the accretion flow is relatively poorly resolved) will have over-estimated the rate of q increase. Secondly, Moeckel & Bate (2010) found that when they followed the evolution of hydrodynamically-created binaries in a cluster with an N-body code, following gas expulsion, the reconfiguration of complex multiple systems led to some evolution of the q distribution towards lower q pairs. Finally, the most recent re-evaluation of the observed ratio statistics of solar type binaries (Raghavan *et al.* 2010) has demonstrated a flatter distribution than that inferred by Duquennoy & Mayor (1991), owing to an over-generous application of incompleteness corrections at the low q end in the earlier work. The combination of these three factors (i.e. relatively small shifts in both the predicted and observed distributions) means that it is not obvious that there really is an 'extreme mass ratio problem' after all.

5. The formation of wide binaries

The separation distribution of binaries around solar type stars is very broad (Raghavan *et al.* 2010, Duquennoy & Mayor 1991) and extends at the wide end to binaries that are close to the separations where they are likely to be disrupted by dynamical interactions in the Galactic field (Jiang & Tremaine 2009). It is, thus, no mystery why the binary distribution rolls over at around 10^5 AU. What is more puzzling, from the point of view of their creation, is why there is a significant population of slightly closer but still ultra-wide pairs (with separations in the range $10^4 - 10^5$ AU). Stars form from Jeans unstable molecular cloud cores with typical dimensions $\sim 10^4$ AU, and so a binary of that separation can only be created from such a core if it is rotating at break-up velocity (whereas cores in reality rotate at a very small fraction of break-up velocity, Goodman *et al.* 1993). Clearly, the creation of binaries at even wider separations is even more problematical.

There are several possible creation routes. For example, the re-configuration of multiple systems can lead to one member being ejected into a wide but still bound orbit (Delgado *et al.* 2004b). Nevertheless, angular momentum conservation implies that very wide outliers are necessarily of very low mass, in contrast to the observed situation. Alternatively, it is possible in principle for a field star to be captured into wide orbit around a binary, though the incidence is expected to be far lower than the observed incidence of ultra-wide pairs. It is notable that in either of these scenarios, the primary of the ultra-wide pair is expected to be itself a binary; however the recent survey of ultra-wide M dwarf binaries by Law *et al.* (2011) finds a normal multiplicity of the primaries. In 50% of cases, the primary is apparently single so that high-order multiplicity is not a pre-requisite for the creation of ultra-wide pairs.

The only mechanism that creates wide pairs without the involvement of a third bound component is that noted in the N-body simulations of Kouwenhoven *et al.* (2010) and Moeckel & Bate (2010) which tracked the N-body evolution of binaries following gas expulsion. In both cases, snapshots of the simulations revealed the existence of instantaneously bound ultra-wide pairs. This is superficially puzzling, since - even by the standards of the expanding cluster - the pairs are extremely ‘soft’ . This raises questions both about the survivability of such binaries and about their creation mechanism, since conventional three-body capture within clusters involves three stars whose trajectories are mutually gravitationally focused and produce binary pairs that are ‘hard’ (i.e. with orbital velocity exceeding the local cluster velocity dispersion). Although intriguing, these studies raised a number of questions about the longevity of the binaries thus produced, as well as the mechanism for their creation.

Moeckel & Clarke (2011) recently undertook a large suite of N-body simulations of clusters which dissolve due to two-body relaxation following stellar dynamical core collapse, taking care to assess the permanence of the binary pairs produced. They found that there are indeed two populations of long-lived binaries: the expected population of hard binaries formed in the cluster core by three-body capture and a comparable population of ultra-wide pairs formed in the outer cluster as it dissolves.

Detailed examination has revealed the mechanism for the creation of the ultra-wide pairs: in any cluster, there is always a population of nearest neighbours that are instantaneously bound. Typically, these are readily broken up by perturbations by other cluster members and their significance is only that a very small fraction of them are eventually hardened by interactions so as to provide a supply of long-lived hard binaries (Goodman & Hut 1993). However, the case of a dissolving cluster is different in that the local stellar density may decline on a timescale that is shorter than the expected timescale for soft binary disruption at that density. Since we have similarity solutions for the decline in cluster density, we can estimate where in the cluster we expect this condition to be fulfilled (in the outer cluster, as observed in the simulations) and can predict how the separation distribution of the permanent soft binaries evolves (at any time, binaries are created at a separation comparable with mean interstellar separation). Furthermore, one can show through simple analytic argument that one expects of order one such binary to form per cluster per decade of separation *independent of N*, a result that is confirmed by analysis of the simulation results.

This last result implies that, in order to explain the fact that a few percent of all solar type stars are in ultra-wide pairs (separation $10^4 - 10^5$ AU), we would need the 'typical' natal cluster to harbour of order ~ 100 stars, this number being compatible with estimates from nearby star forming regions (Lada *et al.* 1991). This may explain why a relatively populous young star cluster, the Orion Nebula Cluster, which contains a few thousand stars, has been observed to be under-abundant in wide binaries compared with the field (Scally *et al.* 1999).

6. An afterword on magnetic fields

We stated at the outset that the last decade has seen a switch from simulations of isolated star forming cores to cluster wide simulations and that this has inevitably involved some compromise in resolution and in the range of physical effects explored. Although all of the results described above relate to unmagnetised simulations, there have been several recent attempts to include magnetic fields (Hennebelle & Teyssier 2008, Price & Bate 2009).

The former study (which was restricted to an isolated magnetised core) posed the provocative question 'Is there a fragmentation crisis?' since it was found that the growth of toroidal fields had important effects in inhibiting fragmentation and binary formation, even in the case of relatively weak fields. For example, it was found that in the absence of large initial fluctuations, there is no fragmentation when the magnetic field exceeds 5% of the 'critical' value (i.e. where magnetic fields can prevent gravitational collapse) and that rapid magnetic braking can even prevent disc formation if the field exceeds $\sim 20\%$ of its 'critical' value. Observed star forming cores, however, have magnetic fields that are close to being 'critical' (Crutcher 1999), leading Hennebelle & Teyssier (2008) to question whether the assumption of ideal MHD is correct or whether there is not a mechanism for accelerated field decoupling during the collapse process. On the other hand, the (cluster scale) simulations of Price & Bate (2009) do produce binaries in the presence of magnetic fields that are globally close to 'critical', suggesting perhaps that differences in the amplitude of initial perturbations and magnetic field morphology may explain the differences with the isolated core simulations. This is clearly an important question, given the undeniable existence of strong magnetic fields in star forming regions, and points to an important new direction for binary formation calculations in the coming years.

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Discussion

W. KLEY: You mentioned circumbinary disk simulations. I assume that they have been isothermal. How would a change in the equation of state alter the results?

C. CLARKE: Nobody has looked at this in detail. However, I would guess that the most important parameter in determining the flow morphology is the ratio of the local sound speed to the binary orbital speed for material at the inner edge of the circumbinary disc.

A. BURROWS: What is the efficiency of star formation in these simulations?

C. CLARKE: That varies from simulation to simulation, depending on how gravitationally bound is the parent cloud. This latter parameter affects the clustering parameters of the resulting stars but seems to have a rather minimal effect on the binary properties.